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Constraints and Categories of Vadose Zone Monitoring Devices

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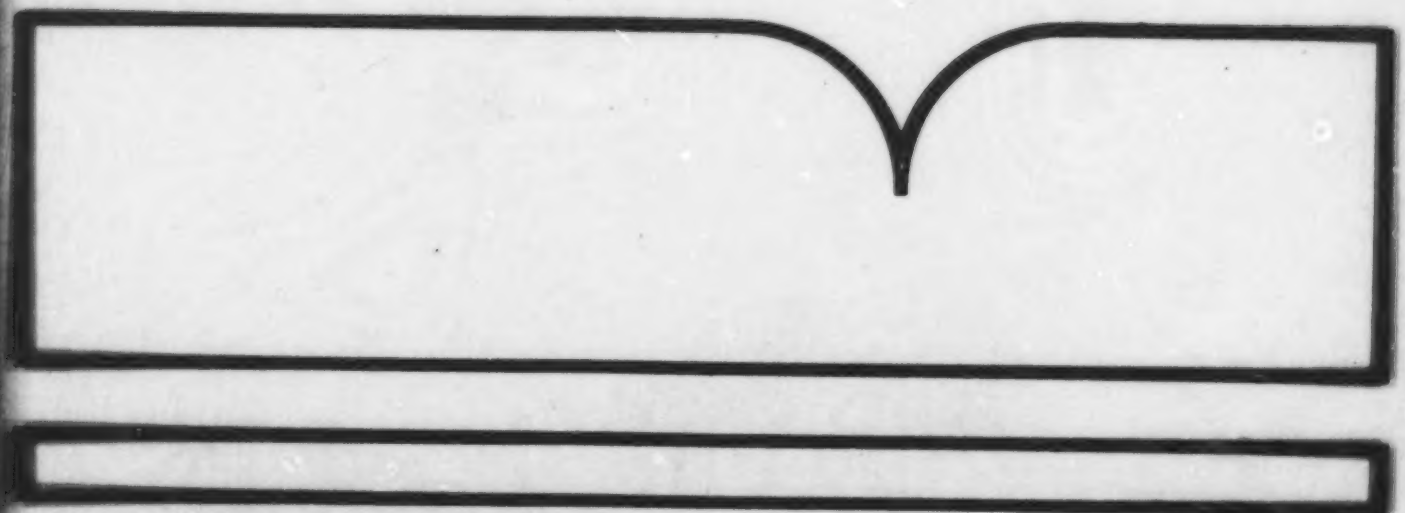

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16. ABSTRACT

Traditional monitoring methods using chemical analysis of ground water samples to detect pollutant migration are being superseded or used in conjunction with innovate approaches. A need to detect pollutants before they reach the water table has drawn interest to vadose (unsaturated) zone monitoring and brought together hydrogeologists, soil scientists and agricultural engineers who have been working on this subject for years.

Recent studies have identified over 50 different types of vadose zone monitoring devices and methods that have optimum utility in varying hydrogeologic settings. In general, measurements made in the vadose zone are trying to define storage, transmission of liquid waste in terms of flux and velocity, and pollutant mobility.

Criteria for the selection of alternative vadose zone monitoring methods are important for the development of site-specific systems. These criteria include: type of site; applicability to new, active, and abandoned sites; power requirements; depth limitations; multiple use capability; type of data collection system; reliability and life expectancy; degree of operational complexity; direct versus indirect methods; applicability to alternate media; effect on flow regime; and effect of hazardous waste on sampling or measurements. Applications of the selection criteria is discussed in Everett et al. (1982a).

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Constraints and Categories of Vadose Zone Monitoring Devices

by Lorne G. Everett, Edward W. Hoylman,
L. Graham Wilson and Leslie G. McMillion

Abstract

Traditional monitoring methods using chemical analysis of ground water samples to detect pollutant migration are being superseded or used in conjunction with innovative approaches. A need to detect pollutants before they reach the water table has drawn interest to vadose (unsaturated) zone monitoring and brought together hydrogeologists, soil scientists and agricultural engineers who have been working on this subject for years.

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Vadose Zone Defined

The vadose zone is the geological profile from the ground surface to the upper surface of the principal water bearing strata. Figure 1 is an idealized cross section showing the vadose and saturated zones. The term "vadose zone" is preferable to the often-used term "unsaturated zone" for this region because saturated conditions are frequently present. The term "zone of aeration" is also often used as a synonym for vadose zone.

The vadose zone has been subdivided into three regions, designated as the soil zone, the intermediate vadose zone, and the capillary fringe (Davis and deWiest 1966). Weathering of native geological material, together with the process of eluviation and illuviation of colloidal materials, to develop more or less well-developed soil profiles is generally recognized to take place and thus defines the limits of the soil zone. Water movement in the soil zone is generally in the unsaturated state, i.e., that state in which the soil water exists under pressures that are less than atmospheric. The principal transport mechanisms associated with unsaturated flow are infiltration, percolation, redistribution and evaporation. Saturated regions may develop in the soil zone in response to surface flooding, especially in soils that contain horizons of low permeability. A large number of monitoring methods for the soil zone have been compiled by Black (1965) in a two-volume set entitled "Methods of Soil Analysis."

The soil zone gradually merges with the underlying intermediate vadose zone through a transition from weathered to generally unweathered native material.

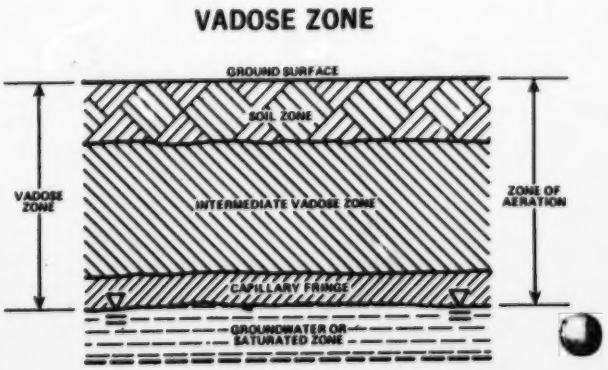

Figure 1. Idealized cross section of vadose and ground water zones

Figure 2, an alluvial basin in California, shows that the intermediate vadose zone is rarely uniform throughout. In some regions it may be practically non-existent, when soils merge directly with bedrock. Water movement through the intermediate vadose zone has been studied by McWhorter and Brookman (1972). Wilson (1979) provides additional information and references regarding the intermediate vadose zone.

The base of the vadose zone, the capillary fringe, merges with underlying saturated material of the principal water bearing formation. This zone is not characterized as much by the nature of geological materials as by the presence of water under conditions of saturation or near-saturation. In general, the thickness of the capillary fringe is greater in fine materials than in coarse deposits. Transient flow in the capillary fringe has been investigated by Taylor and Luthin (1969).

The thickness of the vadose zone will not necessarily be constant as shown in Figure 2. Pumping from the principal water bearing formation will lower the water table and modify the overall thickness of the zone of aeration. Conversely, waste disposal operations commonly create a mound throughout the capillary fringe reducing the thickness of the vadose zone.

Monitoring in the Vadose Zone

Monitoring in the saturated zone utilizes well-defined techniques familiar to hydrologists, geologists, and engineers. Hydraulic conductivity (permeability), storage coefficient and specific yield are parameters derived from well tests that define aquifer characteristics. Pumping tests provide adequate information to assess the storage and water movement through the formation. Chemical analysis of ground water samples generally completes the required information needed to assess the condition of the aquifer. In the vadose zone, where a large percentage of the flow is unsaturated, standard pump tests cannot always be used although researchers are still interested in similar parameters, i.e. storage, transmission of liquid through the strata, and chemical characteristics or pollutant mobility. A wide variety of alternative methods are used to derive information on these vadose zone characteristics. Table 1 gives alternative sampling methods and equipment used to define vadose zone characteristics along with constraint categories discussed by Everett et al. (1982a).

Categories of Vadose Zone Monitoring Techniques

Vadose zone monitoring techniques, i.e., collecting data on storage, transmission of fluids, and pollutant mobility, can be arbitrarily divided into two categories based on whether sample material is removed from the test location. Sampling methods can obtain either liquid or solid material. Extraction techniques of pore fluid from soil samples is dependent on whether inorganics, organics, or microorganisms are under investigation. Liquid sampling methods are dependent on whether fluid is taken from the saturated or unsaturated regions of the vadose zone. A detailed discussion of sampling techniques is given in Wilson (1979).

Non-sampling methods do not remove material from the test location and therefore provide indirect indication of the vadose zone characteristics. They include surface and downhole geophysical methods, numerical, and water budget-type techniques. These methods can be subdivided, depending on the specific property of the vadose zone that is being studied. Alternative methods for determining salinity, infiltration rate, flux, and

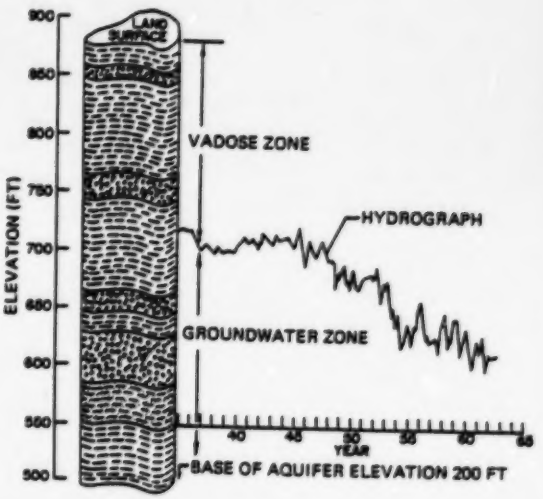

Figure 2. Cross section through the vadose zone and ground water zone (Ayers and Branson 1973)

velocity, using non-sampling techniques, are given in Everett et. al. (1982b).

Constraints on the Operation of Suction-type Sampling Devices

Factors that affect the operation of suction-type devices may be grouped as follows: (1) soil-physical properties, (2) hydraulic factors, (3) cup-waste water interactions, and (4) climatic factors. Specific constraints in each of these categories are summarized in Table 2.

Physical Properties

Soil texture refers to the size distribution of constituent particles, i.e. gravels, sand, silt, and clay. Successful operation of suction samplers requires continuity of pore sequences in the cup with those in the surrounding matrix. When soils are very coarse, particularly when gravels are present, ensuring good contact between the cup and the finer pore sequences may be difficult and the flow continuum may be destroyed. To ensure contact under such conditions, the usual procedure is to place the cup in a segment of an auger hole filled with silica flour.

Soil structure refers to the aggregation of the textural units into blocks. A well-structured soil has two distinct flow regions for liquids applied at the land surface: (1) through the cracks between blocks, i.e. interpedal flow, and (2) through the finer pore sequences inside the blocks, i.e. intrapedal flow. Simpson and Cunningham (1982) have shown that rapid flow of waste water through interpedal cracks may lessen the renovating capacity of the soil because of reduced surface area and contact face. Similarly, because of the rapid flushing of pollutants through larger interconnected soil pores, the movement of such pollutants into the finer pores of the soil blocks may be limited. Because suction-cup samplers collect water from these finer pore sequences, the resultant samples will not be representative of the bulk flow. Thus, Shaffer et al. (1979) concluded that "... surface installed, porous cup soil water samplers are unsuited to test leachate water composite when a highly structured soil is kept in a state of high water content."

A similar problem arises when suction cups are placed in fractured media or in a material containing

Table 1
Summary, vadose zone monitoring techniques—sampling methods

	Type of site		Applicability		Power requirements			Depth limit			Mult use capability		Data collection system			Continuous sampling	
Property	New	Old	Lab	Field	ac	dc	Eng	No	Surf.	<30ft	>30ft	Samp	Meas	Man	Auto	Remote	Yes	No
Pollutant Mobility																		
I. Chemical/microbial properties w/liquid wastes in unsat region																		
A. Solids samples/extraction of pore fluid																		
1. Obtaining solids samples																		
a. Hand auger	•	•		•					•	•		•	•	N/A	N/A	N/A	N/A	N/A
b. Power auger	•	•		•			•		•	•	•	•	•	N/A	N/A	N/A	N/A	N/A
2. Obtaining solution samples																		
a. Hydraulic squeezer	•	•		•				•	•	•	•	N/A	N/A	N/A	N/A	N/A	N/A	N/A
b. Field sat. extract.	•	•		•				•	•	•	•	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C. Lab sat. extract.	•	•		•				•	•	•	•	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B. In-situ pore water samples																		
1. Lysimeters, vac oper	•			•				•	•	•		•	•	N/A	N/A	N/A	•	
2. Lysimeters, vac pres	•			•	•				•	•	•	•	•	N/A	N/A	N/A	•	
3. Lysimeters, high-pres vac	•			•					•	•	•	•	•	N/A	N/A	N/A	•	
4. Filter candle	•			•	•				•			•	•	N/A	N/A	N/A	•	
5. Hollow fiber filters	•		•	•				•	•			•		N/A	N/A	N/A	•	
6. Membrane filters	•		•	•				•	•			•		N/A	N/A	N/A	•	
II. Chemical/microbial properties w/liquid wastes in sat. regions																		
A. Integrated samples																		
1. Wells	•	•		•	•		•	•	•	•	•	•	•	N/A	N/A	N/A	•	
2. Collection pans	•	•		•	•		•		•	•		•		N/A	N/A	N/A	•	
3. Tile outflow	•	•		•				•		•	•	•		N/A	N/A	N/A	•	
B. Depthwise samples																		
1. Profile samples	•	•		•	•		•			•	•	•		N/A	N/A	N/A	•	
2. Multilevel sampler	•	•		•	•		•			•		•	•	N/A	N/A	N/A	•	•
3. Piezometers	•	•		•			•			•	•	•	•	N/A	N/A	N/A	•	

	Sample meas vol		Reliability and life expectancy		Degree of complexity		Direct/ indirect		Media		Effect on flow region		Effect of haz waste type on res	
Property	Point/line	Bulk	Good	Quest.	Simple	Comp	Dir	Ind	Porous	Fract	Yes	No	Yes	No
Pollutant Mobility														
I. Chemical/microbial properties w/liquid wastes in unsat region														
A. Solids samples/extraction of pore fluid														
1. Obtaining solids samples														
a. Hand auger	•		•		•		•		•	•	•			•
b. Power auger	•		•		•		•		•	•	•			•
2. Obtaining solution samples														
a. Hydraulic squeezer	•		•	•	•		•		•			•	•	•
b. Field sat. extract.	•		•	•	•		•		•			•		•
C. Lab sat. extract.	•		•	•	•		•		•			•		•
B. In-situ pore water samples														
1. Lysimeters, vac oper	•		•		•		•		•	•	•			•
2. Lysimeters, vac pres	•		•		•		•		•	•	•			•
3. Lysimeters, high-pres vac	•		•		•		•		•	•	•			•
4. Filter candle	•		•		•		•		•	•	•			•
5. Hollow fiber filters	•			•	•		•		•	•	•			•
6. Membrane filters	•			•	•		•		•	•	•			•
II. Chemical/microbial properties w/liquid wastes in sat. regions														
A. Integrated samples														
1. Wells	•		•		•		•		•	•	•			•
2. Collection pans	•		•		•		•		•	•		•		•
3. Tile outflow		•	•		•		•		•	•		•		•
B. Depthwise samples														
1. Profile samples	•		•		•		•		•	•	•			•
2. Multilevel sampler	•		•		•		•		•	•	•			•
3. Piezometers	•		•		•		•		•	•	•			•

Table 2
Factors limiting the operation of suction-type sampling devices

Soil physical properties	Hydraulic factors	Cup waste water interactions	Climatic factors
1. Contact between cup and soils difficult to maintain in very coarse textured soils (e.g. gravels).	1. In highly structured soils and fractured material, the composition of fluid in cracks may differ from that in pores. Cups sample only from small pores. Consequently, cup samples may not be representative of "average" fluid.	1. Samples cannot be obtained when soils dry to the point that soil-water suction is great enough to allow air to enter cups when applying vacuum. 2. For very wet conditions fluid will move more rapidly in layer pores and cracks. Because of time lag, sample for cups may not be representative.	1. Solids moving with fluid may plug cups. 2. Bacteria may plug cups. 3. Trace metals may be attenuated during flow through cups. 4. Sorption of NH_4-N may occur. 5. Sorption of some organics (e.g. chlorinated hydrocarbons) may occur.	1. In frozen soils, the tension of unfrozen water is greater than air entry value of cups. 2. In freezing-thawing soils, the unit may shift in the profile and lose contact.

solution cavities. For these cases, high flow velocities through conducting channels may drain solutions before the cups can obtain a representative sample.

Hydraulic Factors

It is well established (Everett 1981) that suction-cup samplers fail as the soil-water suction increases to the point that air bubbles enter the cups. The soil-water pressure equivalent to this point is about -0.8 bar. In practice, however, many units fail at a pressure of about -0.5 bar. This appears to be a serious limitation in operating suction samplers. However, as Hillel (1971) pointed out, "Though the suction range of 0 to 0.8 bars is but a small part of the total range of suction variation encountered in the field, it generally encompasses the greater part of the soil wetness range."

Also, as noted under soil physical properties, when waste water is applied to a well-structured soil, the initial flow velocity may be quite high. Consequently, samples collected from cups installed within soil peds may not be representative of the bulk flow at that time.

Cup-Waste Water Interactions

An initial concern with lysimeters was that plugging may occur with time, limiting their effective lifetime (U.S.EPA 1980). In fact, this was the principal reason for not recommending suction samplers for monitoring at hazardous waste landfills and impoundments. Johnson, Cartwright, and Schuller (1981) conducted laboratory studies to evaluate the plugging of suction lysimeters with particulate matter in landfill leachate. They noted a distinct loss in yield from samplers in direct contact with leachate. A concomitant decrease in yield of identical lysimeters placed beneath a landfill was not observed, however. Apparently, particulate matter moving through the soil profile is filtered out before contacting the cups.

Dazzo and Rothwell (1974) conducted laboratory studies to determine the extent to which fecal coliforms are strained during suction-cup sampling. They observed a 100- to 10,000,000-fold reduction in fecal coliform in manure slurry during sampling, and 65 percent of the cups yielded coliform-free samples. Dazzo and Rothwell concluded that ". . . porcelain cup water samplers do not yield valid water samples for fecal coliform analyses."

Tsai et al. (1980) conducted laboratory studies to determine the attenuation of trace metals during movement of liquid through ceramic cups. They observed that nickel, copper, zinc, iron, manganese, and lead were consistently reduced by 5 to 10 percent during percolation through cups. Wagner (1962) found that NO_3-N was not adsorbed by cups, but sorption of NH_6-N did occur. Hansen and Harris (1975) found evidence that phosphorus was strongly adsorbed by cups, but concluded that sorption is only serious when ". . . the ceramic sorptive capacity is significantly greater than that of the adjacent soil."

Because a major concern at land treatment areas is the fate of organic pollutants, the effect of organic-cup interactions on sampling results is of paramount importance. According to Morrison and Tsai (1981), "Laboratory studies by Tsai et al. (1980) found that several pesticide species were substantially reduced when leached through a 0.32 cm thick ceramic cup with a pore size of 2.5 micron. Concentrations of the chlorinated hydrocarbons pp DDD', pp DDE', and pp DDT" were reduced 90 percent, 70 percent and 94 percent respectively."

Climatic Factors

A major factor limiting the operation of suction samplers (and tensiometers) in frozen soil is that the soil water suction is about -0.8 bar. This means that the air entry value of the cups is exceeded and samples cannot be obtained. Another effect of freezing temperatures is that some soils tend to heave during freezing-thawing. Consequently, suction-cup samplers may be displaced in that soil profile, resulting in a break in contact. Another undocumented problem that conceivably could occur is freezing of samples within the cups, precluding bringing them to the surface. In addition, if the cups are full when frozen, the cups may be fractured during expansion of the freezing liquid.

Flow velocity in porous media is inversely related to the viscosity of the fluid moving in the pores. An increase in temperature of a waste water, e.g. by hot ambient temperatures, would consequently increase the flow rate in soils at a disposal site. If the flow rate is excessive, suction samples may not obtain a true sample of the bulk fluid because of time lag effects.

Alternative Methods for Vadose Zone Sampling

When constraints limit the use of suction-type sampling devices, three alternatives are suggested for compiling data in the vadose zone. These are: (1) soil sampling, (2) sampling at the water table, and (3) vapor sampling.

The recently issued standards for land treatment areas (U.S. EPA 1982) specify soil sampling in addition to sampling pore fluids directly by suction sampling devices. Consequently, if these devices cannot be used for some reason, conducting soil sampling as carefully as possible is all the more important. The major disadvantage of soil sampling, however, is that it is essentially a destructive method; the same location cannot be resampled as with suction lysimeters. Consequently, delineating changes through time in constituents of interest is difficult. Since samples are required only from a relatively shallow depth, sampling can be carried out using hand augers or simple power equipment. Tube-type augers have been used extensively for soil sampling. The Veihmeyer tube is an example of a tube sampler used by soil scientists. E.R. de Vera et al. (1980) suggested using Veihmeyer tubes (Figure 3) when sampling for hazardous waste constituents. The end of the steel tube is beveled and sharpened to facilitate insertion into the soil. A drive hammer is used to force the tube to the desired depth and an intact core is obtained. Another technique is the so-called "dry tube" method developed by Dunlap et al. (1977). This method consists of augering a hole to the desired depth and forcing a dry tube core sampler into the sampling region. Contamination problems are avoided because drilling fluid is not used. Care in sample storage and preservation is important to prevent loss or dissipation of constituents of interest, especially when sampling for organics. Fenn et al. (1977) describe techniques for extracting pore water from unsaturated soil, including a hydraulic squeezer. Dao and Levy (1978) describe a simple centrifugation method for extracting soil solution in the laboratory. Extraction of volative organics from undisturbed soil cores required displacing pore gases with an inert gas, such as helium, and analyzing the displaced gas with a gas chromatograph (GC).

Many proposed and existing land treatment areas are probably in regions where water tables are in close proximity to the lower limit of the treatment zone. For such sites, shallow well installations are highly recommended to permit sampling near the water table. Such samples will represent fluid that has passed through the vadose zone. The preferred method is the multilevel sampler, developed by Pickens et al. (1978) (Figure 4). This sampler is particularly advantageous in that shallow plumes can be easily identified by locating sampling ports at staggered intervals beneath the water table. In addition, ports can be included above the low water table level to facilitate sampling during periods of water table rise, and also gas sampling. All-metal construction should be employed instead of the usual PVC to avoid interference when sampling for organics.

Finally, at sites where volative organics are being disposed of, installing screened well points beneath the treatment zone to collect soil gas samples may be desirable. (This approach may be desirable even when suction lysimeters cannot be used.) Multilevel samplers, of all-metal construction to avoid contamination, can also be used to collect soil gas samples. Gas samples can be analyzed directly in the field using portable GC units.

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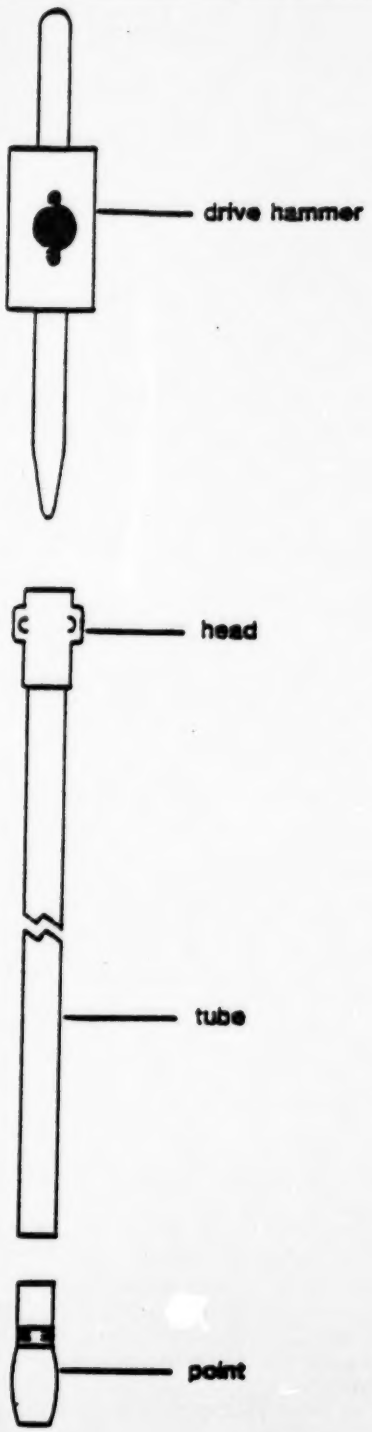

Figure 3. Veihmeyer tube

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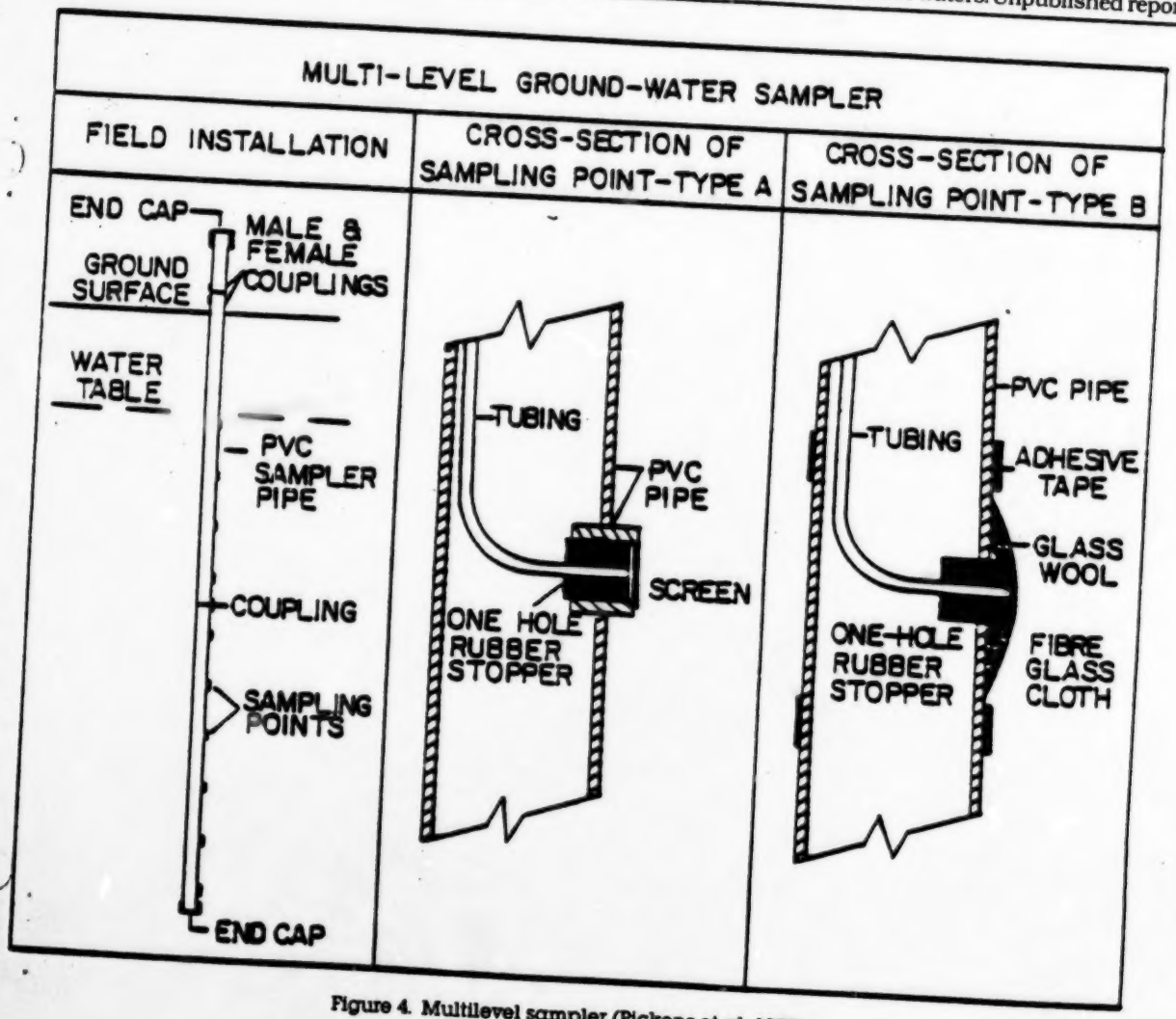

Figure 4. Multilevel sampler (Pickens et al. 1978)

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Biographical Sketches

E.W. Hoylman (Kaman Tempo, Natural Resources Program, 816 State Street, P.O. Drawer QQ, Santa Barbara, CA 93102) is a senior hydrogeologist who received his B.S. in hydrology and geology from the University of Hawaii in 1970 and his M.S. in geology in 1974. He is a co-author of several papers developing vadose zone monitoring concepts. His recent research focuses on application of geophysical methods for use in the vadose zone.

Lorne G. Everett (Kaman Tempo, Natural Resources Program, 816 State Street, P.O. Drawer QQ, Santa Barbara, CA 93102) is the manager of the Natural Resources Program at Kaman Tempo, Santa Barbara, California. In addition to authoring more than 75 professional papers, Dr. Everett is the author of the handbook entitled "Ground Water Monitoring."

L.G. Wilson (Water Resources Research Center, University of Arizona, A.E. Douglas Building, #28, Tucson, AZ 85721) is a hydrologist with the Water Resources Research Center at the University of Arizona, Tucson, Arizona. Dr. Wilson is the author of the state-of-the-art report titled "Monitoring in the Vadose Zone: A Review of Technical Elements and Methods."

L.G. McMillion (U.S. EPA, Environmental Monitoring Systems Lab., P.O. Box 15027, Las Vegas, NV 89114) is a senior hydrologist with the EPA Environmental Systems Laboratory, Las Vegas, Nevada. McMillion is the EPA project officer who has been responsible for major research programs directed toward establishing national monitoring strategies and ground water monitoring guidelines for energy extraction sites.

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